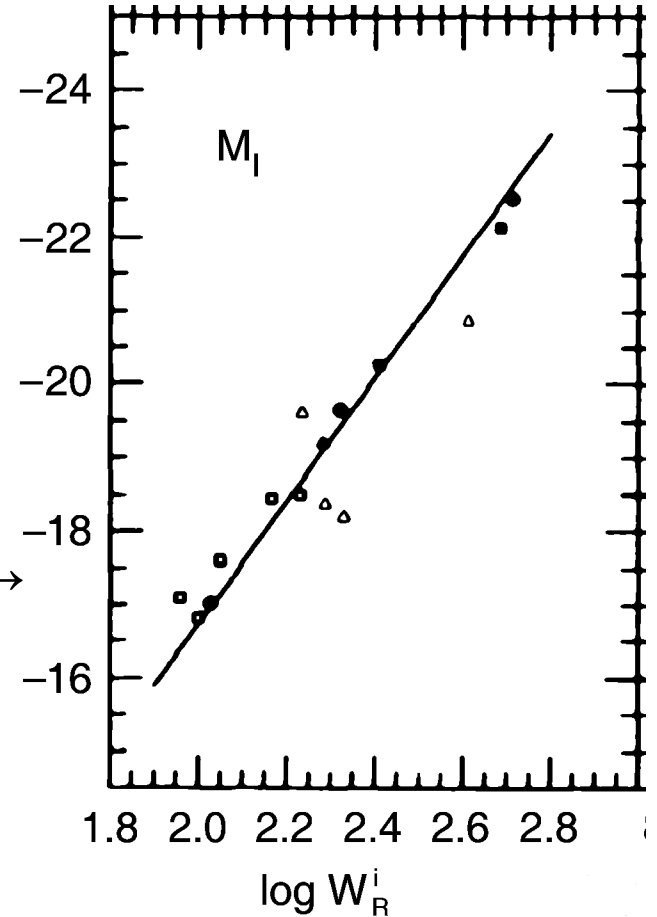
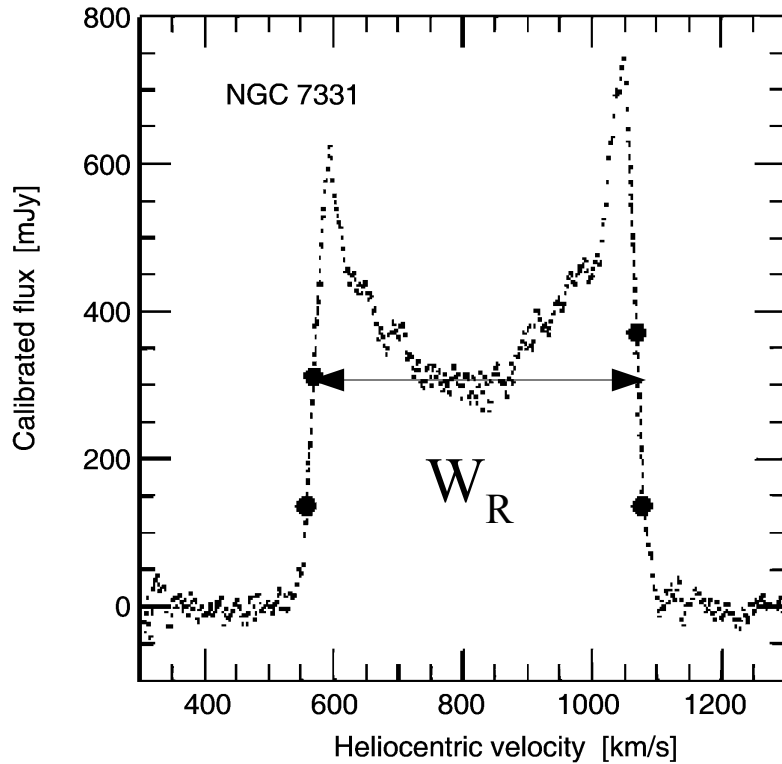


# More Galaxies

- Scaling relations
- Extragalactic distances
- Luminosity functions
- Nuclear black holes

# Tully-Fisher relation

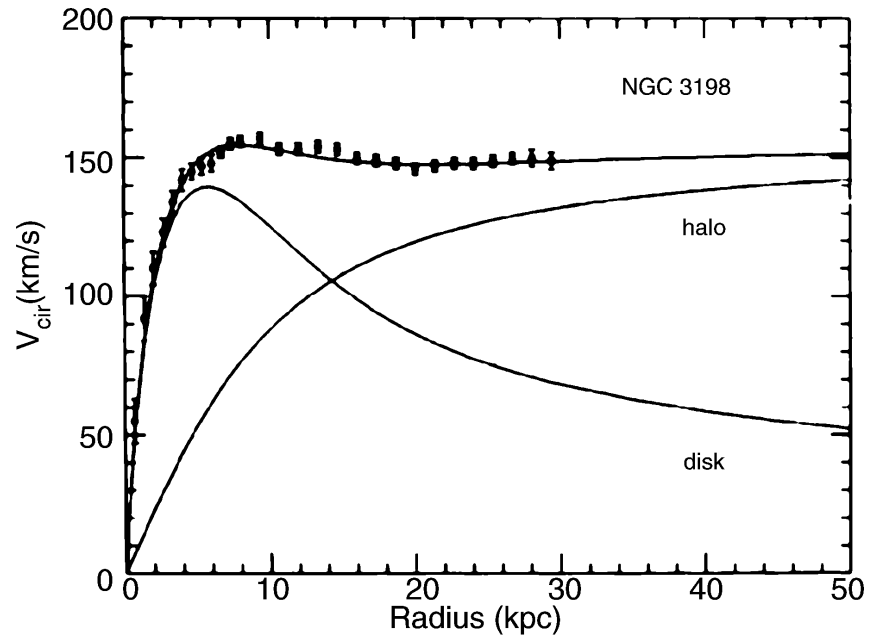
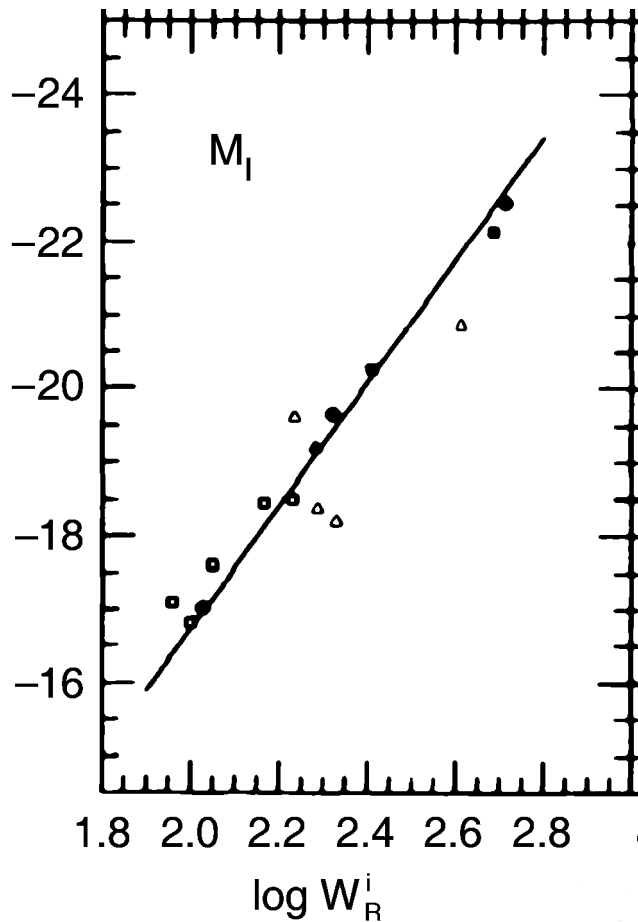


- In spirals, luminosity  $L \sim v_{\max}^{\alpha}$  with  $\alpha \sim 4$ .

# Tully-Fisher relation

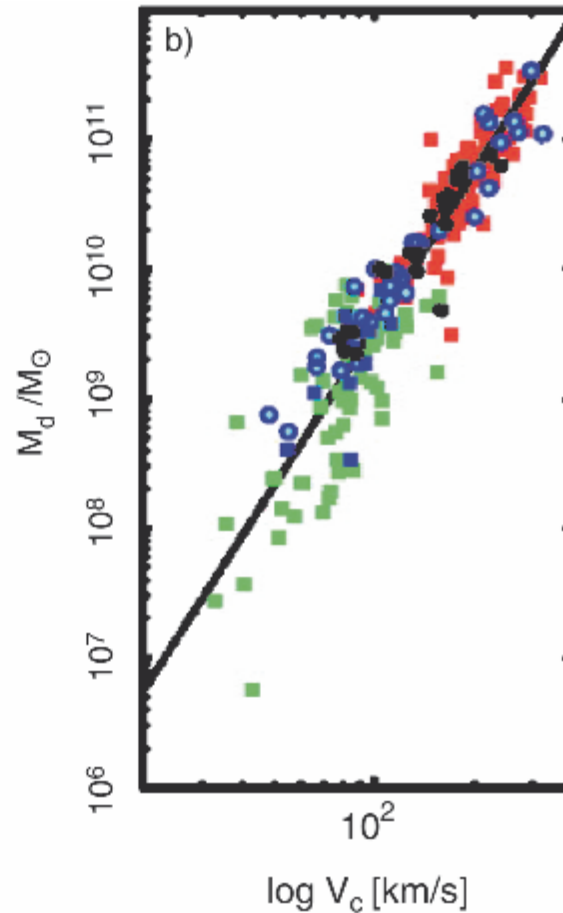
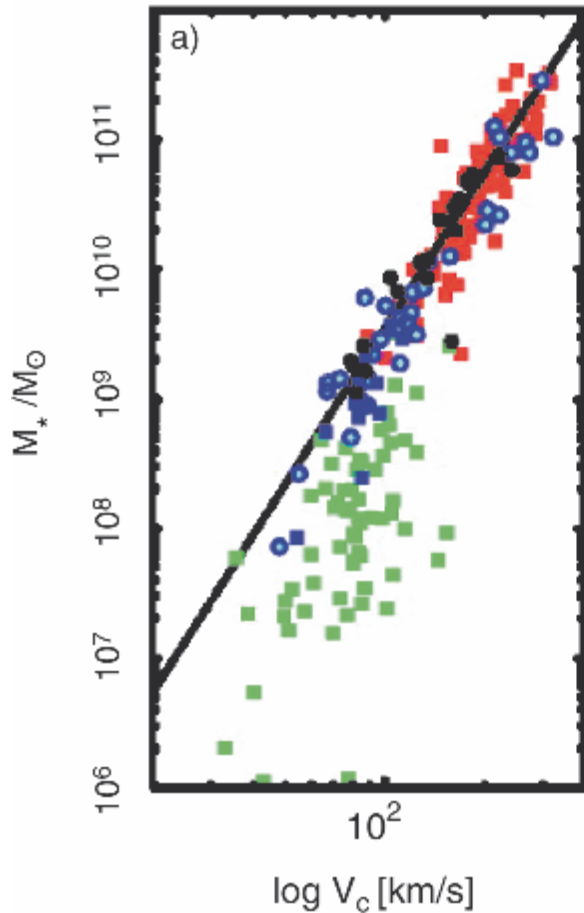
- From Newton,  $M = v_{\max}^2 R/G$
- Multiply by  $L/M$ ,  $L = (M/L)^{-1} v_{\max}^2 R/G$
- Empirically, spirals (except LSB) seem to have similar surface brightness profiles, so write  $L = \langle I \rangle R^2$ , where  $\langle I \rangle$  is average surface brightness.
- Square second equation, substitute  $R^2 = L/\langle I \rangle$ , and find
$$L = (M/L)^{-2} (G^2 \langle I \rangle)^{-1} v_{\max}^4 \quad \text{or} \quad L \sim v_{\max}^4$$
- Conclude Tully-Fisher is OK if  $M/L$  and  $\langle I \rangle$  are the same for all spirals.  $\langle I \rangle = \text{constant}$  is OK. But for dark matter,  $M \sim R$ , so  $M/L$  needs to be defined at a particular radius. Use  $D_{25}$ , this is OK since surface brightness profiles are similar.
- Tully-Fisher implies there is a good correlation between dark matter halo and visible matter.

# Tully-Fisher relation



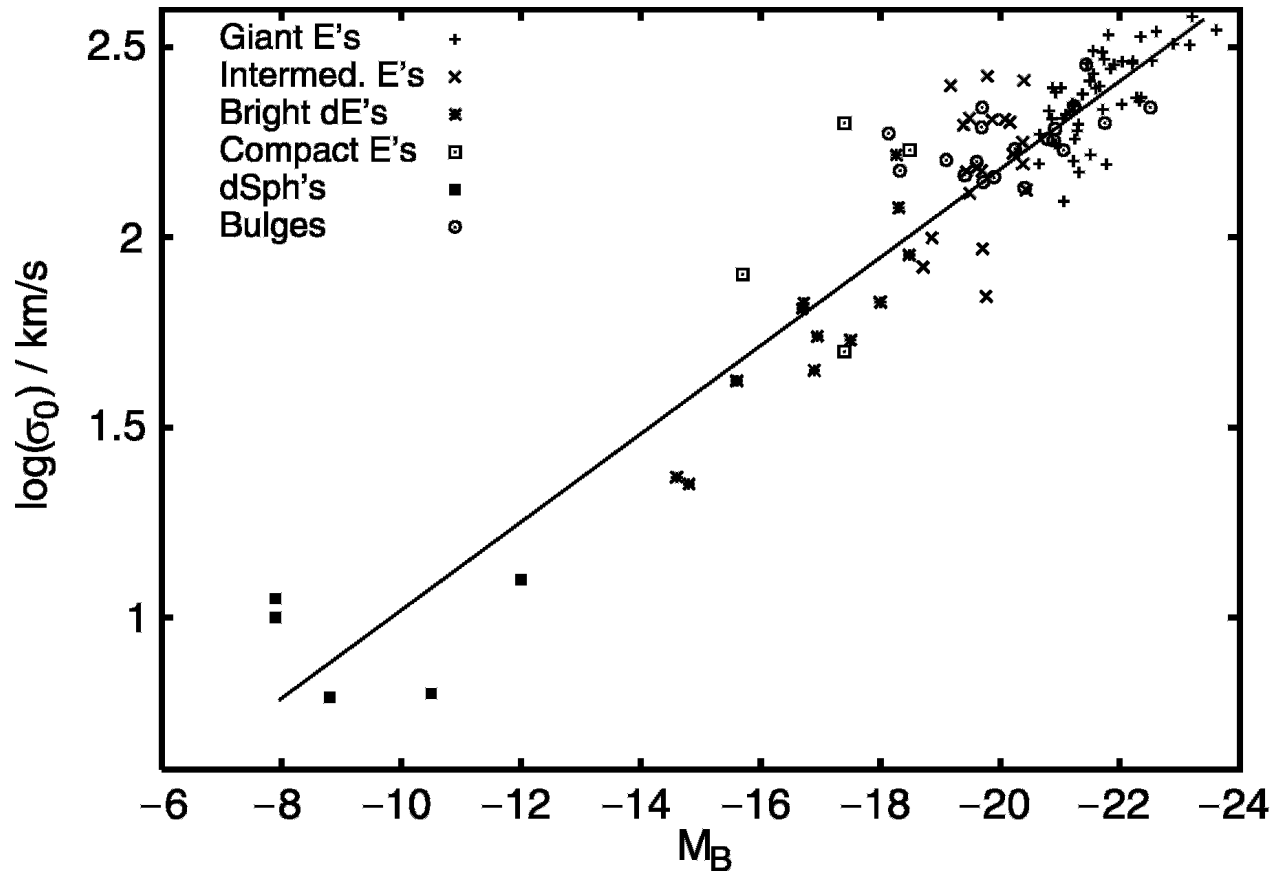
- Luminosity is determined by visible matter (duh)
- Width of rotation curve is determined by both visible and dark matter, but more by dark matter.
- Correlation requires close connection between properties of luminous and dark matter.
- Quantitatively, this connection means that  $M(R)$  is determined by  $L$ .

# Tully-Fisher relation



- Tully-Fisher can be cast as a relation between  $v_{\max}$  and mass.
- Correlation is tighter if total baryonic mass including gas is used.
- Thus, total mass - including dark mass - is determined by visible mass.

# Faber- Jackson relation



- $L \sim v^4$  relation works for ellipticals if we use velocity dispersion instead of  $v_{\text{max}}$ . However, the scatter is larger. This suggests that another parameter is important.
- With 2 parameters, need at least 3 observables. The “fundamental plane” for elliptical galaxies is a relation between effective radius ( $R_e$ ), average surface brightness within  $R_e$

( $\langle I \rangle_e$ ), and velocity dispersion ( $\sigma_0$ ), 
$$R_e \sim \sigma_0^{1.4} \langle I \rangle_e^{-0.85}$$

# Fundamental plane

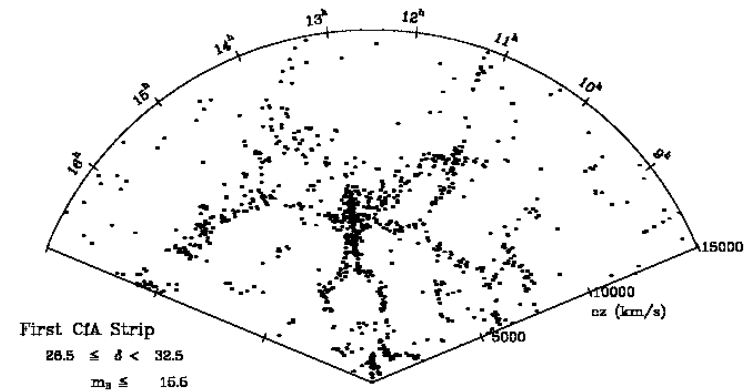
- From Newton,  $M \sim \sigma^2 R$ , by definition,  $L \sim R^2 I$
- Take ratio  $R^2/R$  find  $R \sim (L/M)(\sigma^2/I)$
- Assume  $M/L \sim L^a \sim R^{2a} I^2$  then  $R \sim \sigma^{2/(2a+1)} I^{-(a+1)/(2a+1)}$
- Want  $R \sim \sigma^{1.4} I^{-0.85}$  so  $a = 0.214$
- Thus, fundamental plane is OK if  $M/L \sim L^{0.21}$
- $M/L \sim L^{0.25}$  leads to  $R \sim \sigma^{1.33} I^{-0.83}$  which is consistent with the data.
- Note no mention of dark matter, because dark matter is less important in the inner regions of ellipticals.

# Uses of galaxy relations

- Using Tully-Fisher,  $L \sim v_{\max}^\alpha$ , one can find the luminosity of a galaxy by measuring the velocity profile of the galaxy – which is distance independent. Thus, Tully-Fisher can be used to estimate distances to galaxies by comparing measured flux with estimated luminosity.
- One can use Faber-Jackson or the fundamental plane to find distances, but usually one uses the  $D_n$ - $\sigma$  relation that relates the velocity dispersion to the diameter within which the average surface brightness is a specific value. Then one calculates the distance by comparing the measured angular size of the galaxy with the estimated physical diameter  $D_n$ .



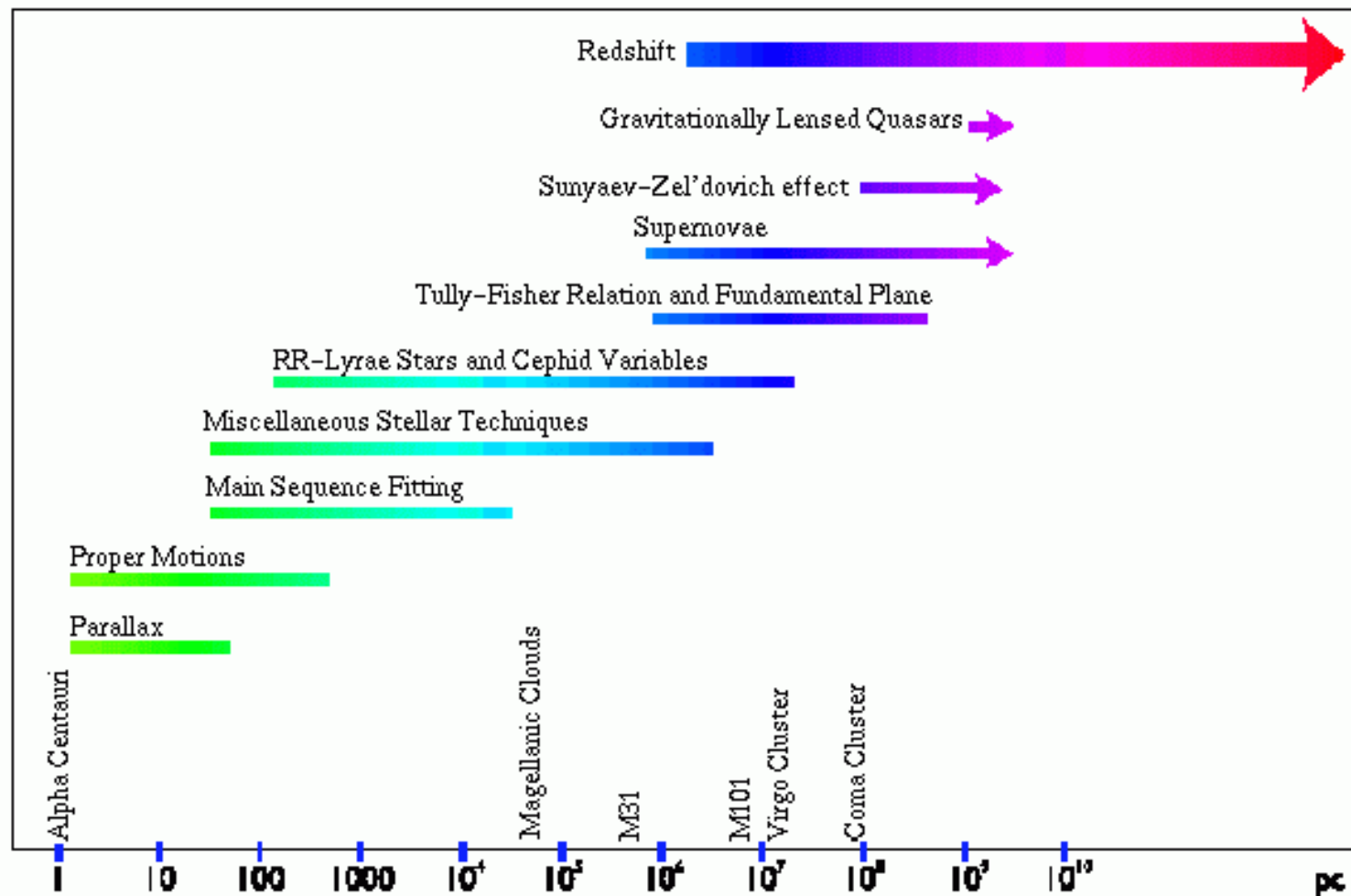
# Extragalactic distances



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- Most commonly used distance estimator is the Hubble expansion  $v = H_0 D$ , measure velocity (redshift) by taking a spectrum, then divide by  $H_0$ .
- Distance estimate is inaccurate if  $v$  has a component not due to Hubble expansion – peculiar velocity. Galaxies can be formed with peculiar velocity or acquire one from gravitational force from nearby galaxies which is particularly important in clusters.
- Fractional error due to peculiar velocity decreases as expansion velocity increases. Redshift distances are accurate beyond 50-100 Mpc, but not closer than  $\sim 10$  Mpc.
- Distance measurements are built up via a ladder: parallax used for close objects, then various techniques applied for **overlapping** distance intervals and calibrated versus each other by measuring the distances to individual galaxies containing multiple classes of distance estimators.
- Need to extend distance ladder to 50-100 Mpc to measure  $H_0$  accurately.

# Extragalactic distances

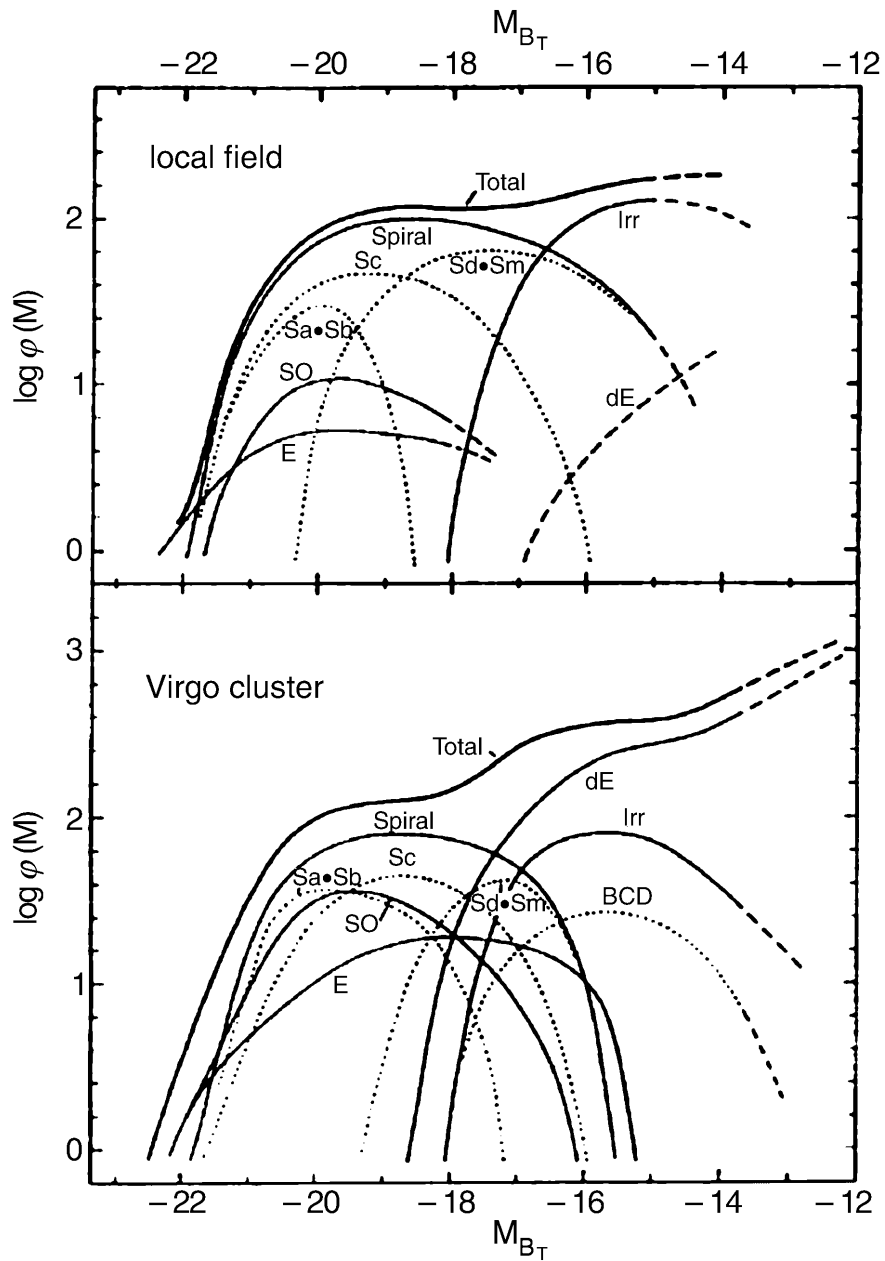


**Figure 3.2:** The different distance estimators. This seemingly simple plot shows a grand overview of our efforts to measure distances in the Universe. Adapted from [Rowan-Robinson, 1985] and [Roth and Primack, 1996].

# Luminosity functions

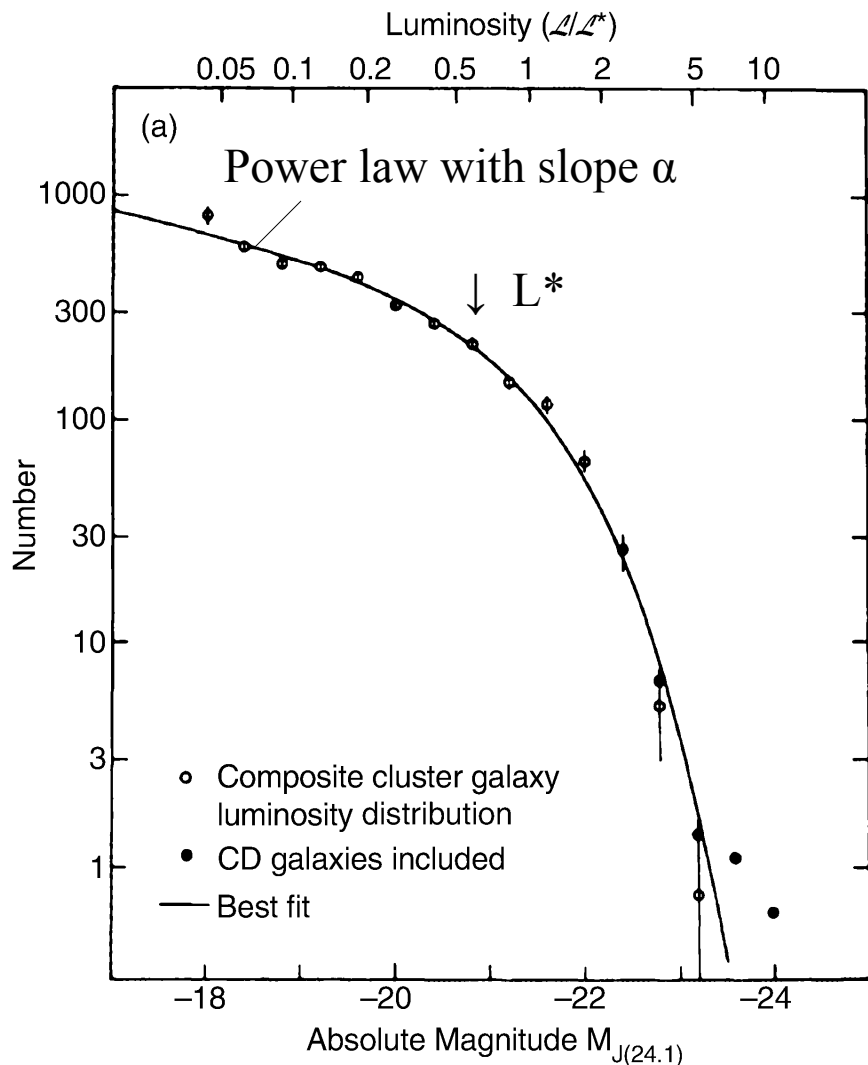
- Luminosity function, how does the number of galaxies vary as a function of galaxy luminosity
- $\Phi(L)dL$  = number of galaxies in luminosity interval  $[L, L+dL]$ . Can be a density (i.e. divide number by volume) or simply a number (say for all galaxies in the Virgo cluster). Often  $\Phi$  is specified in terms of absolute magnitude,  $M$ , instead of  $L$ .
- Sometimes, the integral luminosity function is presented – number of galaxies more luminous than  $L$ .
- Measuring  $\Phi$  is straight forward for a cluster, all galaxies are at the same distance. Need to be careful about removing foreground/background objects, but these can be identified by redshift. Also,  $\Phi$  may be incomplete at low  $L$ .
- Measuring  $\Phi$  in the field is more difficult. Need to either construct a volume limited sample or correct for fact that more luminous galaxies can be detected at larger distances (Malmquist bias).

# Luminosity functions



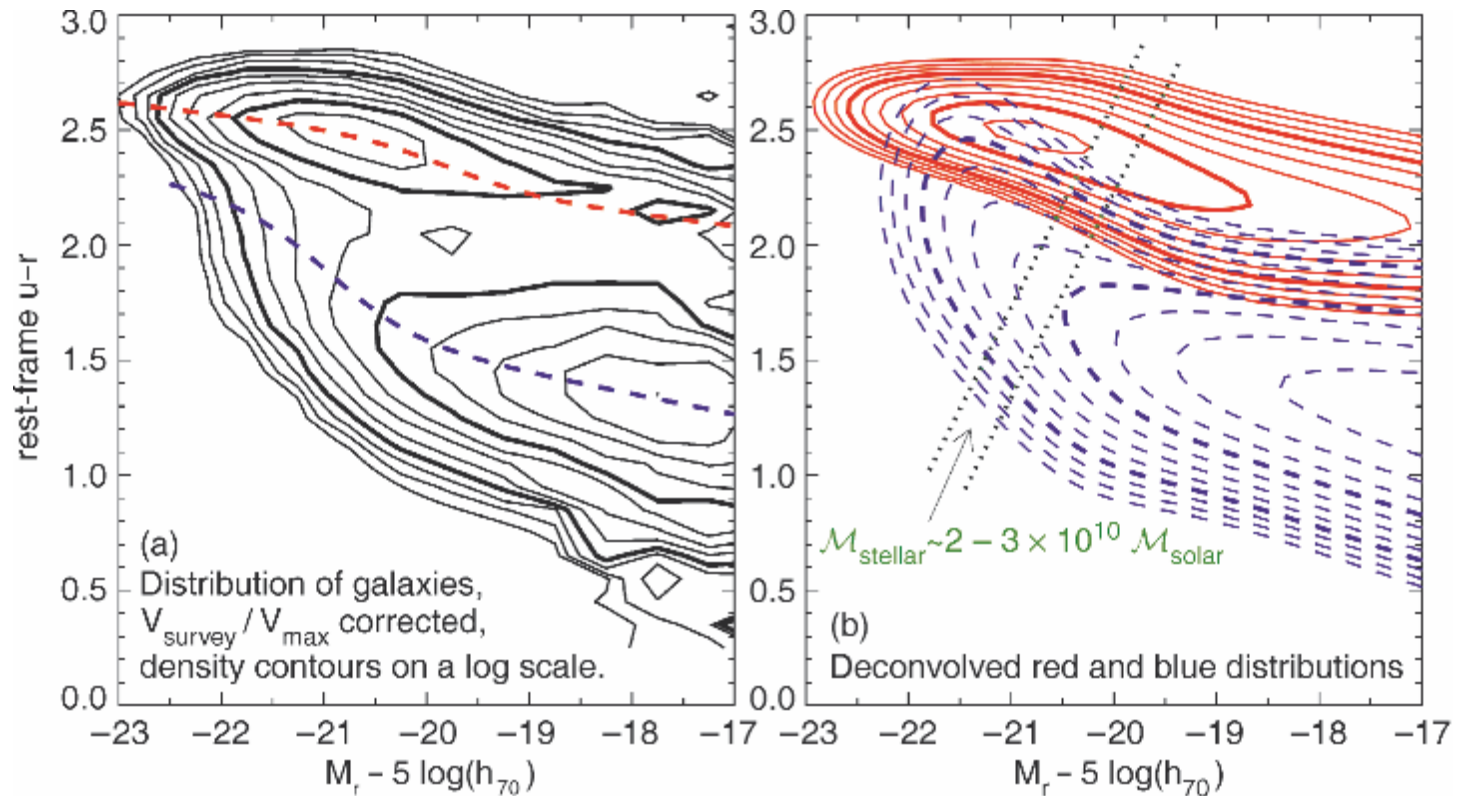
- Different types of galaxies have different luminosity functions. Luminosity function gives quantitative information about distribution of luminosities and relative number of galaxies of different types as a function of luminosity.
- Luminosity function is different in different environments. E.g. compared to the field, clusters have fewer spirals and more ellipticals particularly at very high and very low luminosities.

# Luminosity functions



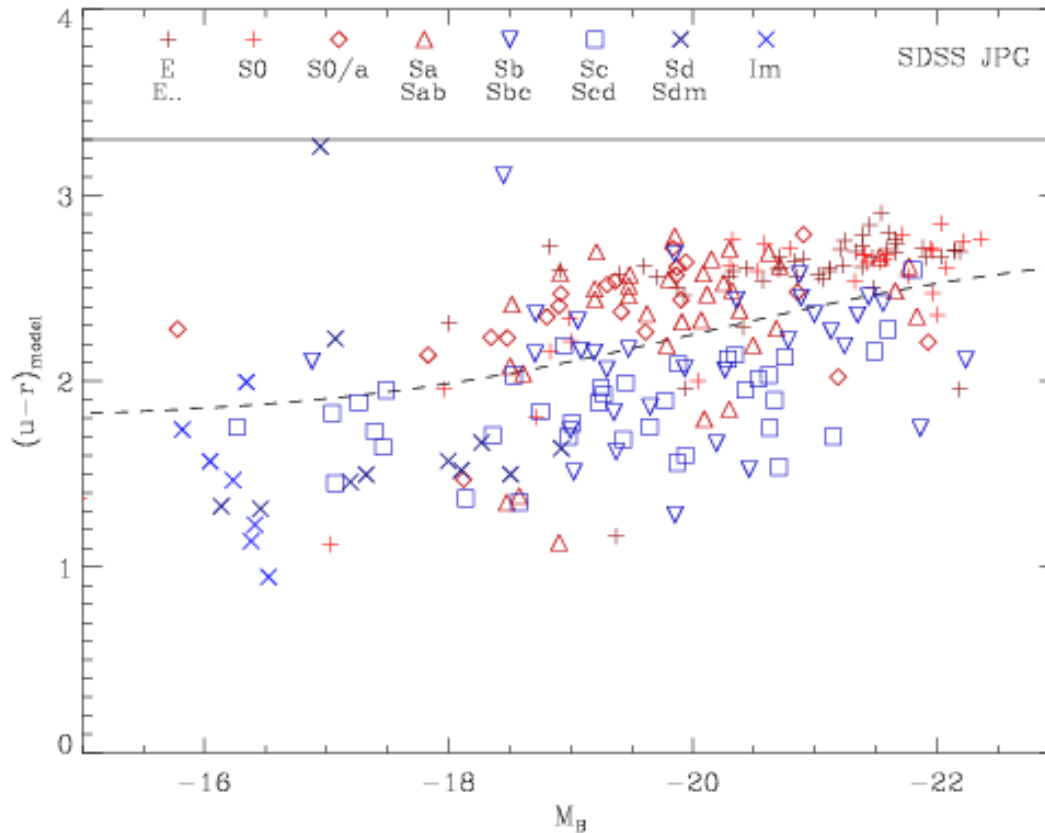
- If one looks at a very large number of galaxies, the luminosity function appears to follow the Schechter function:
  - Power law (slope  $\alpha$ ) at low luminosity
  - Exponential cutoff above  $L^*$
- There is no simple physical explanation for the Schechter function.
- Individual groups of galaxies, say clusters, follow the Schechter function only roughly.

# Color-magnitude diagram



- Two distinct peaks in galaxy CMD: dim/blue versus bright/red.
- Can model distribution as pair of Gaussians at each  $M$  with centroids and widths that vary with  $M$ .

# Color-magnitude diagram



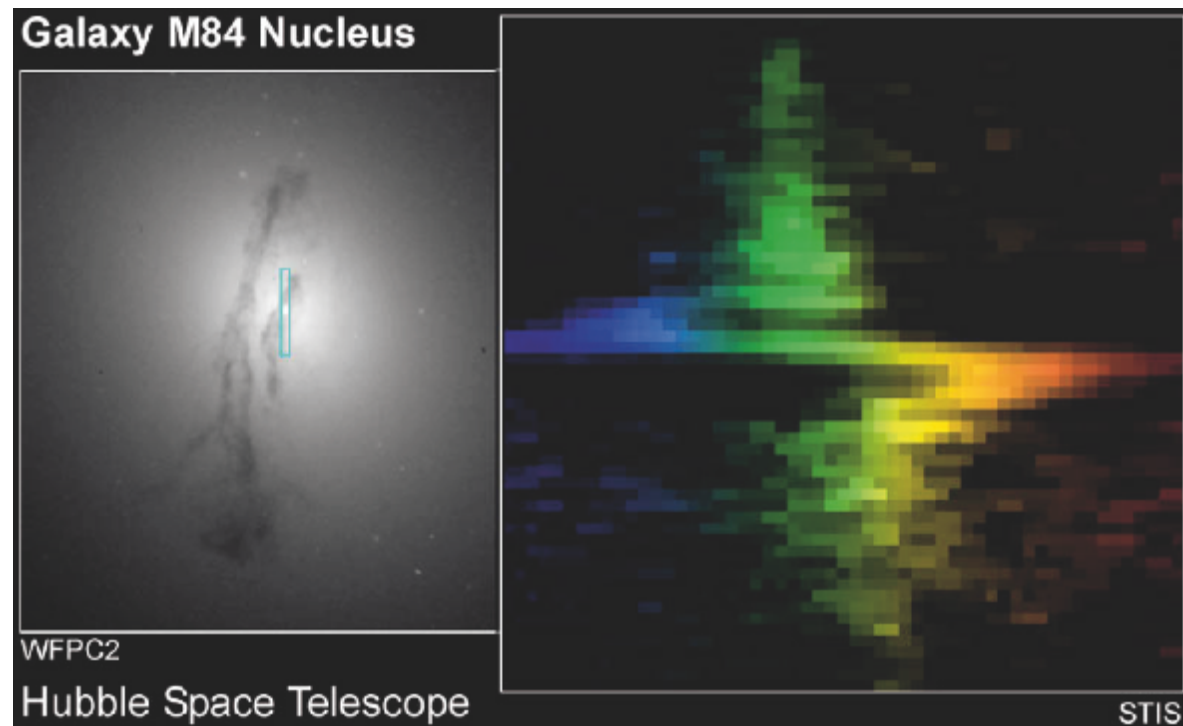
- Bimodal distribution roughly reproduces traditional classification (James et al. 2008).
- Fraction in “b” region: E=0.24, S0=0.21, S0/a=0.42, Sa,ab=0.52, Sb,bc=0.81, Sc,cd=0.93, Sd,dm=0.94, Im=1.00

# Black holes at the centers of galaxies

- Size of black hole is Schwarzschild radius =  $2GM/c^2$
- Angular size of BH at center of Milky Way is  $\sim 6$  micro-arcseconds. Too small to resolve for now, but the Event Horizon Telescope hopes to do this via VLBI at  $\sim 400$  GHz within a decade.
- “Radius of influence” is radius within which the BH gravitational field produces a Keplerian orbital speed equal to the velocity dispersion of the surrounding stars,  $r_{\text{BH}} = GM/\sigma^2$ .
- For  $M = 10^6 M_{\text{Sun}}$ ,  $\sigma = 100$  km/s,  $D = 1$  Mpc, we find  $r_{\text{BH}} = 0.1''$ .
- So, we need to be able to measure velocity profiles in regions about  $0.1''$  on a side. This became possible with the Hubble Space Telescope.



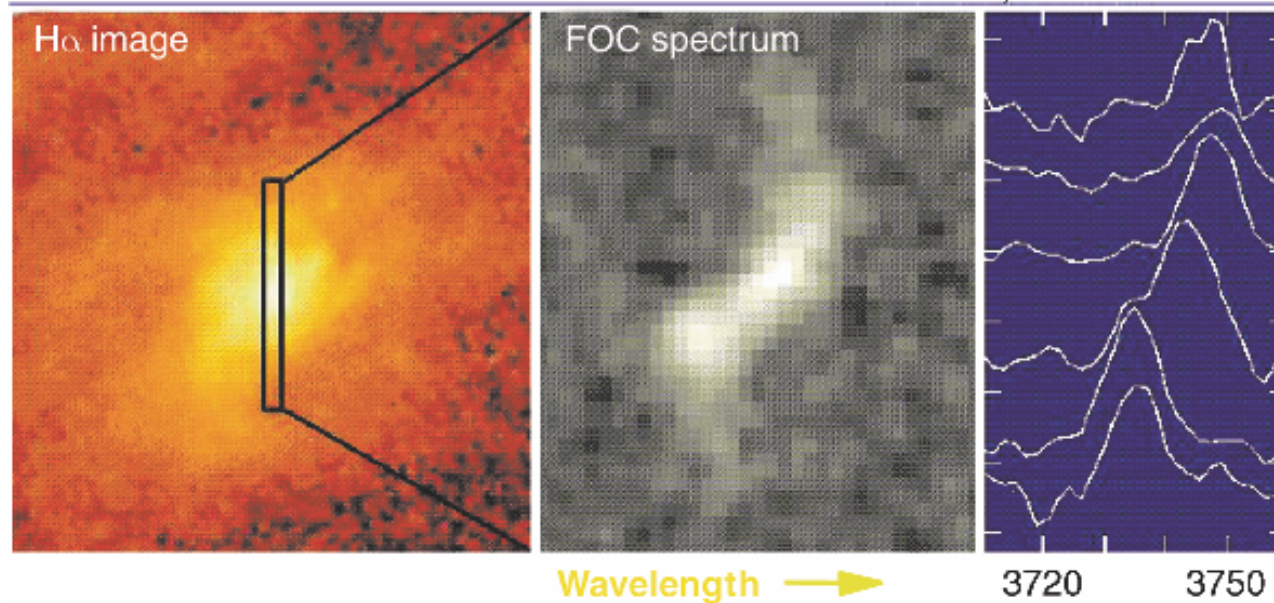
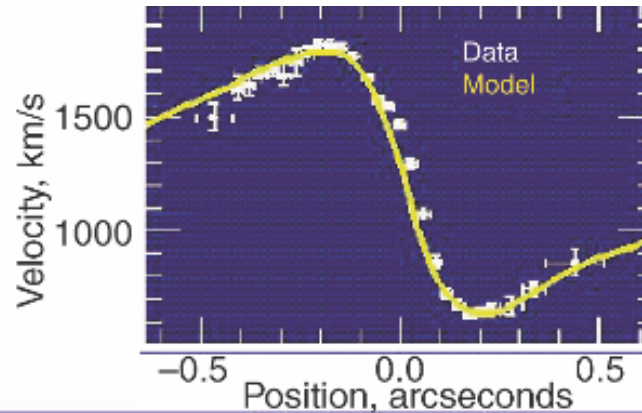
# Black holes at the centers of galaxies



- STIS produces a 2d image with wavelength on one axis and position along the slit on the other. Slit of STIS (Space Telescope Imaging Spectrograph) is placed across nucleus of galaxy. STIS is setup to record wavelengths around an emission line ( $H\alpha$ ,  $[O II]$ ).
- Spectrum from each spatial position is the sum of spectra from all the stars within a small rectangular region on the sky.
- Shift in centroid of the emission line reflects motion of stars around the central black hole.
- Black hole mass can be calculated from magnitude and position of velocity shifts.

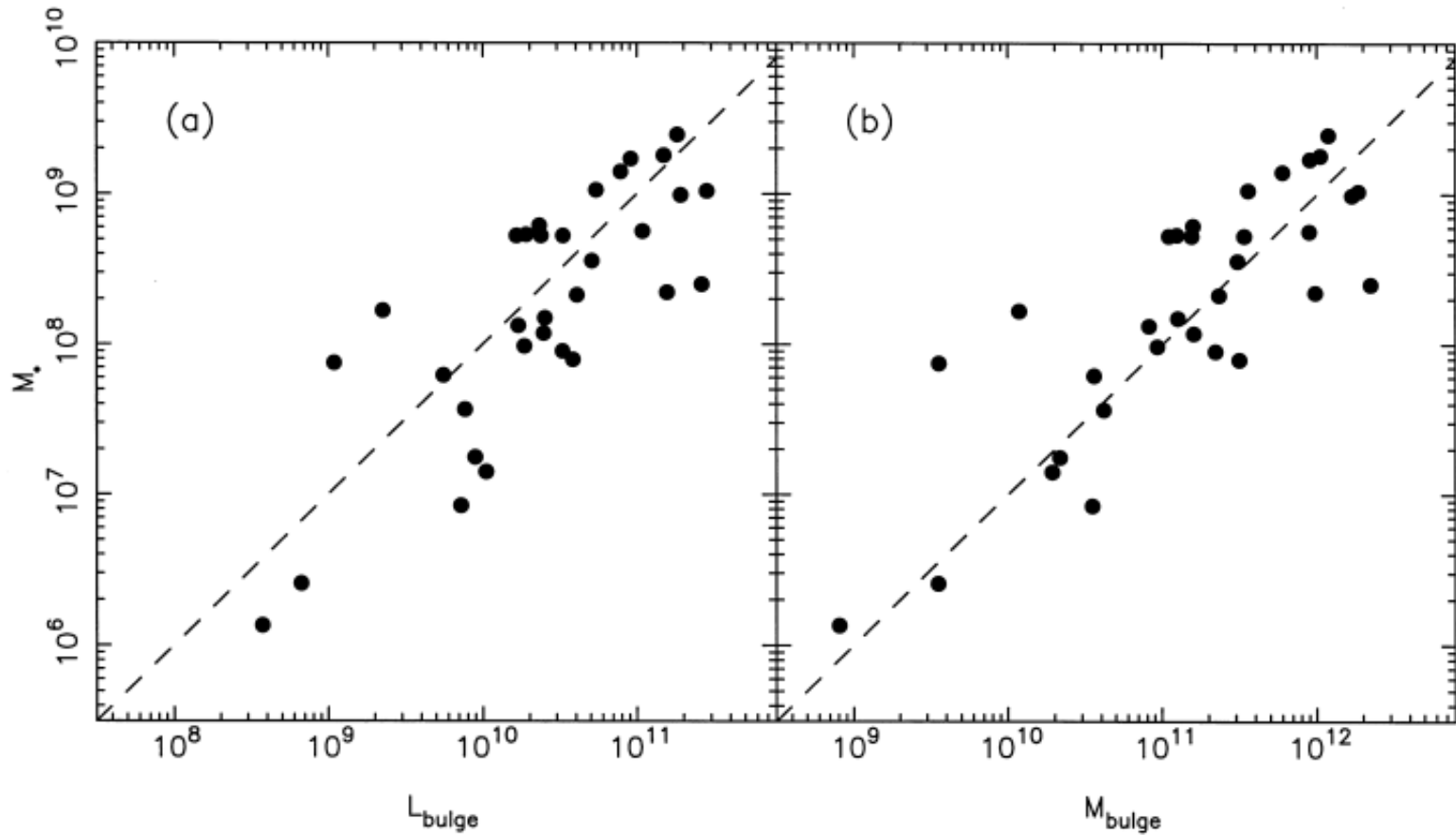
# Black holes at the centers of galaxies

Velocity Profiles  
in the M87 Core



HST has measured BH masses for many galaxies (some also done with VLBI observations of masers).

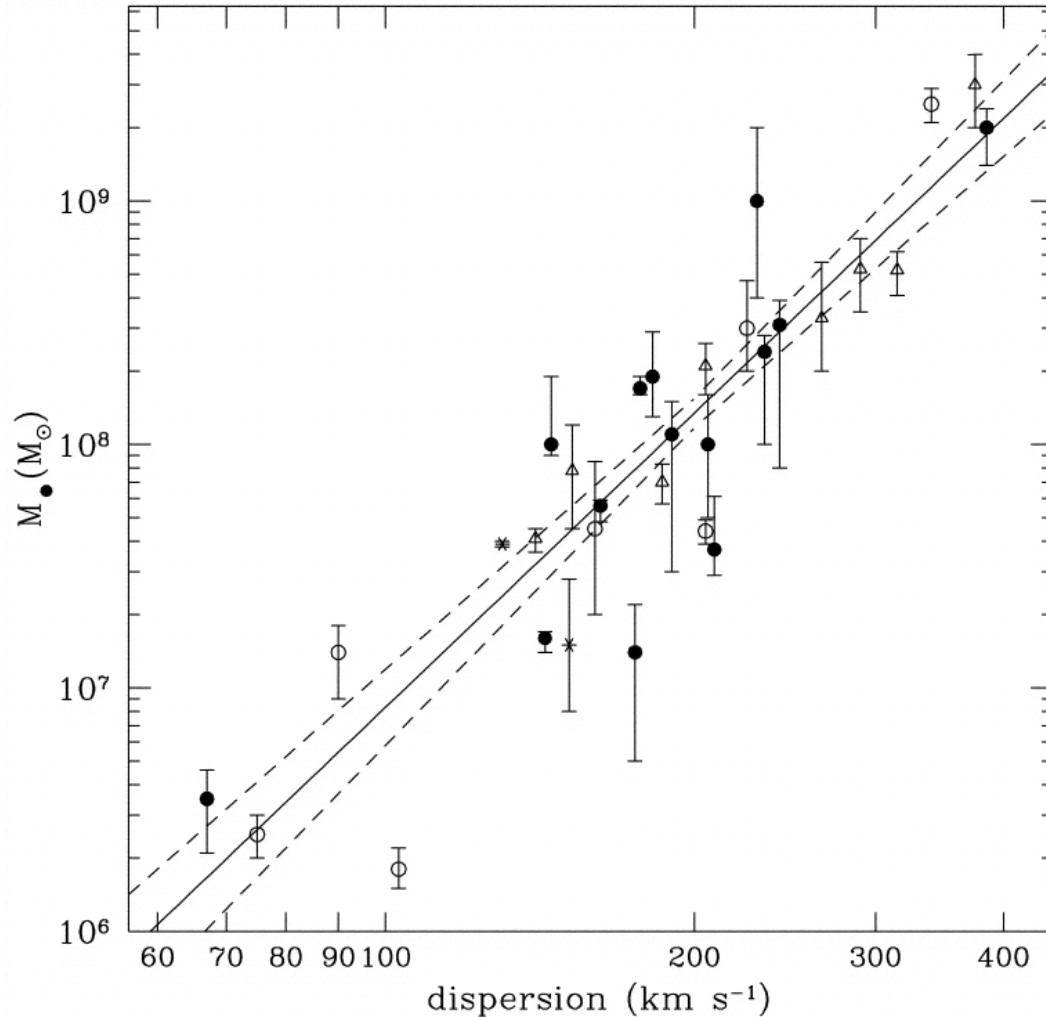
# Black holes at the centers of galaxies



BH mass is correlated with properties of the host's bulge.

$$M/M_{\text{Sun}} = 0.01 L_{\text{Bulge}}/L_{\text{Sun}} \quad \text{and} \quad M = 0.001 M_{\text{Bulge}}$$

# Black holes at the centers of galaxies



Best correlation is with velocity dispersion of the bulge,  
 $M \sim \sigma^a$  where  $a = 4.0 \pm 0.3$

# Black holes at the centers of galaxies

- The  $M$ - $\sigma$  relation indicates a link between the evolution of a galaxy and that of the black hole at its center.
- The physical origin of the relation is still being debated.

# For next class

- Keep a list of terms you don't understand and e-mail it to [philip-kaaret@uiowa.edu](mailto:philip-kaaret@uiowa.edu)
- Read 3.9-3.10
- Work on HW #3 due Wednesday 9/5